Underground Explosions Are Music to Their Ears

In the current era of no nuclear testing, subcritical experiments are helping to safeguard the nation’s nuclear stockpile.

BAGPIPE, Oboe, Clarinet, and Piano could be the elements of an avant-garde musical ensemble. At Lawrence Livermore, however, they are the names of recent explosive tests conducted deep under the Nevada desert by Laboratory physicists and engineers. The tests are aimed at providing important data to experts watching over the nation’s nuclear weapon stockpile.

In the Livermore experiments, chemical high explosives are detonated next to samples of weapons-grade plutonium (plutonium-239) to obtain new insights about plutonium and its alloys in the ensuing microseconds. The tests, conducted at the Department of Energy’s 3,500-square-kilometer Nevada Test Site, are subcritical. That is, no critical mass is formed, so no self-sustaining nuclear fission chain reaction occurs as it does in a nuclear detonation. The experiments are permitted within the Comprehensive Test Ban Treaty signed by President Clinton in 1998.

Indeed, subcritical tests have become largely accepted internationally for ensuring the safety and reliability of a nation's nuclear force without resorting to nuclear testing. Russia has been conducting subcritical tests involving both weapons-grade plutonium and uranium since 1995 at its Novaya Zemlya test site near the Arctic Circle.

Lawrence Livermore's heavily instrumented experiments provide data on the behavior of plutonium in a strongly shocked state and how that behavior differs from plutonium that has aged over decades inside a nuclear warhead. "We need to better understand how the aging of plutonium could affect the safety or performance of a weapon," says Livermore physicist Dick Lear. He explains that the accumulation of alpha particles (helium nuclei) produced by the radioactive decay of plutonium atoms is thought to cause imperfections in the material's crystalline structure and thereby possibly affect its performance. To investigate the consequences of aging, subcritical tests compare the behavior of newly machined plutonium with that obtained from old, dismantled warheads.

The tests focus on ejecta and spall, phenomena that are thought to affect the performance of a nuclear warhead, specifically that part of the warhead called the primary. Ejecta are a violent spray of plutonium particles that are propelled from a material's surface when it is compressed by a powerful shock wave. Spall is the breakup of plutonium from the explosive shock wave reflected back from the surface.

Tests Provide Real-World Data

The Livermore tests, together with those performed by Los Alamos National Laboratory, play an important role in DOE's Stockpile Stewardship Program to ensure a safe and reliable nuclear weapons stockpile without underground nuclear testing. Stockpile stewardship depends in great measure on advanced computer simulations of weapon performance and materials aging. Subcritical experiments provide the actual data about the behavior of plutonium and thus are useful for improving computer simulation codes, enabling them to more accurately predict any problems with the nation's aging stockpile.

The Nevada tests are an important complement to hydrodynamic experiments on mock warheads conducted at Lawrence Livermore's remote Site 300 test facility in California. While similar to subcritical tests, the hydrodynamic experiments do not use plutonium. Because plutonium is the most enigmatic element in the periodic table (see *S&TR*, June 2000, pp. 15–22), tests using its surrogates cannot accurately answer all the questions scientists have about the behavior of plutonium in a warhead.

The Livermore tests are conducted by the Laboratory's Engineering and Defense and Nuclear Technologies directorates with support from Bechtel Nevada Corp. and AlliedSignal/Federal Manufacturing and Technologies. Livermore researchers share their experimental results with their Los Alamos colleagues.

The subcritical tests are conducted at the U1A complex of the Nevada Test Site, located about 140 kilometers northwest of Las Vegas. The complex

The U1A complex at the Nevada Test Site consists of several buildings and instrumentation trailers from which scientists monitor experiments conducted underground.

consists of several buildings and instrumentation trailers from which scientists monitor experiments conducted in tunnels mined some 290 meters underground. According to Lawrence Livermore engineer Dave Conrad, staging subcritical tests underground is ideal because it minimizes the tests' environmental impact. Conrad, who serves as Livermore's test director and project leader, also points out that underground testing costs far less than designing, building, certifying, and using an aboveground, reusable chamber.

Tunnels Carved Underground

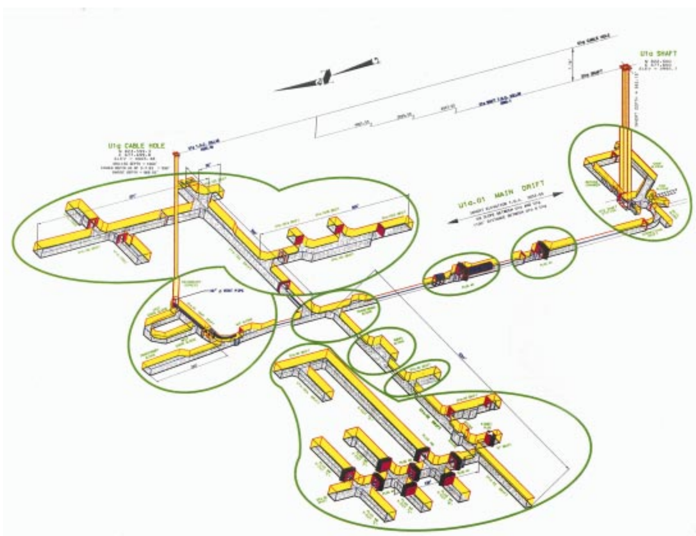
The underground complex consists of several main tunnels (called drifts), each about one-quarter of a kilometer long, and a series of small experimental alcoves branching off from them. The alcoves are also called zero rooms, from the "ground zero" parlance of the nuclear test era. The downhole environment is surprisingly comfortable, with well-lit rooms, concrete floors, tall ceilings, and lunchrooms.

Both Livermore and Los Alamos have designated testing areas in the complex. Los Alamos scientists conduct experiments about every 15 months, while Livermore currently conducts its tests every six weeks, thanks to the use of expendable steel vessels that confine debris from the experiment.

The complex's main vertical shaft is equipped with a mechanical hoist to transport workers and equipment. The shaft was originally mined in 1968 for an underground test that was later canceled. In 1988, the shaft was reopened and a 445-meter horizontal tunnel was mined south of the shaft for a low-yield Los Alamos nuclear test. The test, called Ledoux, was conducted in 1990, two years before President Bush announced a nuclear test moratorium that remains in effect. A second vertical shaft about 305 meters away, constructed in 1991–92, provides cross ventilation, utility access, and emergency egress.

In 1996, Lawrence Livermore started mining its first downhole experimental area, called the 101 drift, using the same mining techniques as those for subway construction. The drift and three small experimental alcoves were completed about 10 months later. The mined areas were stabilized with 5-meter-long steel rods drilled into the tunnel walls, secured with epoxy cement, and sprayed with a slurry of fibercrete, material similar to concrete. The Holog, Bagpipe, and Clarinet test series were all conducted in their assigned alcoves, which afterwards were permanently sealed.

Last year saw the completion of Livermore's second drift, called the 102 minicomplex. Requiring nearly two years to mine, the minicomplex consists



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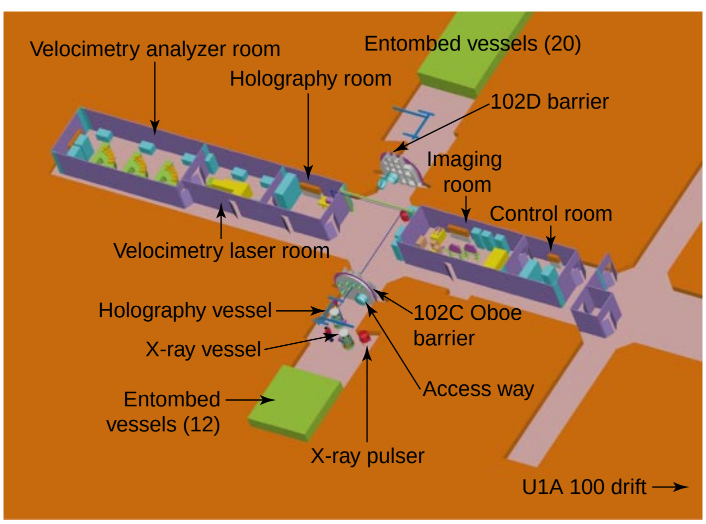


Livermore's 102 minicomplex was completed last year. It consists of a suite of diagnostic rooms and two experimental alcoves dedicated to the Oboe and Piano test series.

of a main drift (82 meters long, 7 meters wide, 6 meters high) and two reusable experimental alcoves (23 and 27 meters long; both are 6 meters wide by 5 meters high). The first alcove is planned to accommodate up to 12 Oboe experiments conducted in steel confinement vessels and one Piano experiment that is possibly too large for a vessel. The second alcove is planned to accommodate 20 additional Oboe experiments and another Piano-like experiment.

Equipment typically used for making subway tunnels was used to carve out Livermore's underground test facilities.

Holography Provides 3-D View

The high-speed diagnostic instruments used in the experiments are similar to those found in research facilities back at Livermore. The primary diagnostic is a laser-based imaging system that captures the cloud of plutonium ejecta flying out from the shocked surface at the moment of explosion (called shock breakout). The film of this experiment is actually a hologram, which, when projected with a laser, allows experimenters to "walk through" a cloud of plutonium particles in three dimensions. The hologram provides data on the size, shape, number, and velocity of the particles. High-speed cameras also record images of the shocked plutonium over time.

Other instruments, also in regular use at Livermore, complement the holography data on plutonium ejecta. The Fabry–Perot interferometer (see *S&TR*, July 1996, pp. 12–19) examines the change of position (and inferred mass and velocity) of particles trapped on a gold foil by measuring the wavelength shift of laser light reflected from the moving foil surface. Also, the rate at which ejecta hit a set of piezoelectric "pins" is recorded.

Radiography experiments look at another phenomenon, plutonium spall. Like an echo, the shock wave caused by high explosives is reflected back from

One of two experimental alcoves in the 102 minicomplex during construction. Workers are installing the utilities required to stage and diagnose subcritical tests.

the plutonium surface. Depending upon the shape of the shock wave, the plutonium can develop cracks in its crystalline structure or even beg in to break into pieces. Radiography instruments determine the dependence of spall characteristics on shock-wave geometry and changes in pressure.

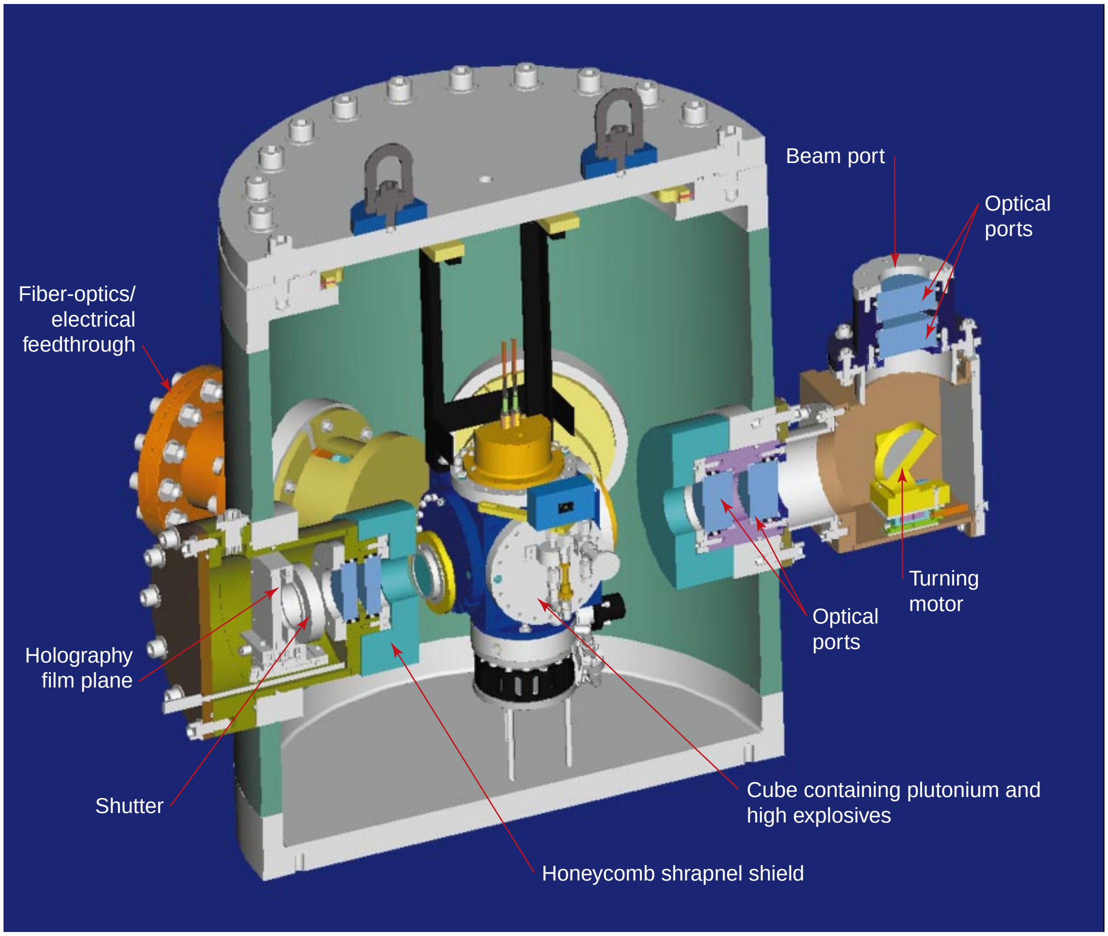
Currently, the x-ray equipment used on the subcritical tests cannot penetrate materials as deeply as scientists would like. But moving underground a giant machine, such as that at Livermore's Flash X-Ray Facility, is simply not possible, given the cramped shafts and the limited real estate downhole. Therefore, a Livermore team is building an x-ray machine that will be powerful enough for the tests and small enough to be transported and set up underground.

Conrad notes that because of the wide-ranging use of optics in experiments, dust is a major enemy. Unfortunately, dust is a natural attribute of the belowground work environment, especially mining activities. The Livermore team uses a host of techniques to keep dust at bay, including air filtration systems, shoe cleaning machines, and sticky tape on floors.

Holog Test Was First

The first Livermore subcritical test, consisting of two experiments, was conducted in September 1997. It was named Holog, after the major holographic diagnostic technique that was used to examine ejecta. Because Holog was the first experiment, scientists paid special attention to understanding the physics of the explosions and the effects on the containment barrier to the alcove.

One year later, Livermore conducted its second subcritical test. Code-named Bagpipe, this set of four experiments was designed to



This cutaway of a steel vessel shows how laser-based imaging equipment is configured to obtain information on ejecta at the moment of detonation. When illuminated with a laser, the exposed film, actually a hologram, allows experimenters to "walk through" a cloud of plutonium particles in three dimensions.

investigate both ejecta production and spall at different pressure regimes. "Bagpipe confirmed that we can successfully field a broad suite of diagnostics on subcritical tests," says Lear. "It gave us confidence to design more complex experiments."

The February 1999 Clarinet test consisted of three experiments that were evaluated by a larger array of diagnostic packages than were used previously. Diagnostic techniques included Fabry–Perot velocimetry, holography, pins, and radiography.

Two of the Clarinet experiments primarily used holography to examine the effects of aging on plutonium. The two were identical in every way except for the age of the plutonium. The size and distribution of ejecta particles resulting from the shock wave in the two plutonium materials were captured on holographic film and analyzed. From the two holograms, scientists inferred changes due to the aging process.

Oboe Inaugurated Minicomplex

Beginning in September 1999, the Oboe test series inaugurated the new 102 minicomplex, where expendable steel vessels that completely confine the experiments were first used. These steel vessels make it unnecessary to carve out a separate alcove for each experiment. The alcove is checked for plutonium leakage after an experiment, and if there is no contamination, workers reenter, move the used steel vessel to the rear of the alcove, and entomb it in concrete at least 30 centimeters thick. Preparations then begin on the next experiment.

"We were looking for ways to do the experiments better, faster, and cheaper," says Conrad. "We asked ourselves if a steel vessel could serve as a miniature zero room, with diagnostic equipment located just outside."

Underground Tests Earn High Safety Marks

In many ways, subcritical tests at the Nevada Test Site are similar to those that have been conducted safely for years at Lawrence Livermore's Site 300 research facility. However, Livermore managers have adopted many new safety procedures for the Nevada tests because plutonium has been introduced, testing is being conducted underground, the diagnostic systems are remotely controlled from above ground, and several diverse organizations, each with its own work culture, are involved.

"The underground work environment is congested and there are many potential hazards," says Livermore test director Dave Conrad. Fortunately, planning for Livermore's first subcritical tests was begun during the introduction of Integrated Safety Management, the Department of Energy's program to ensure the highest safety performance. Following the tenets of the safety program required a review of every activity, from mining to experiment setup, before it was undertaken.

The careful preparation has clearly paid off. For example, during the two years of construction activities related to the newest underground minicomplex, called the 102 drift, there were no major injuries or any involving lost time. Safety continues as the highest daily work priority, and quarterly safety walkthroughs are conducted with representatives from the Department of Energy, Lawrence Livermore, and Bechtel Nevada.

A number of safety systems ensures safety to workers and the environment. For example, a computerized safety interlock system of 87 sensors keeps track of the location of workers downhole. Another system continually samples the underground air quality. For added safety, each worker and visitor carries a portable breathing apparatus for emergencies and certain underground areas have been designated emergency shelters.

Plutonium and high explosives are shipped separately from Livermore and then assembled into an experimental package at the Device Assembly Facility located about 16 kilometers from the subcritical test complex (see *S&TR*, May 1998, pp. 23–25). From there, the experimental packages are trucked to the complex and lowered for transport to the experimental alcove.

A major emphasis is on keeping the plutonium used in the tests completely confined. "We take great care that no plutonium will ever leak out into the general environment," says Conrad. The experiment team's first commandment, he says, is that "not one atom of plutonium shall be released to any uncontrolled environment as a result of the experiment."

The containment plan for the current Oboe series of experiments uses the time-tested concept of nested barriers: first there is the expendable steel vessel in which the experiment is conducted; then the experimental alcove, with its locked and temporarily sealed crawl tube; and finally, a large concrete and steel barrier enclosing the drift. Lawrence Livermore safety experts account for the remote possibility that plutonium could seep into the alcove from a crack in the vessel or a seal failure on one of the vessel's ports. In that case, the alcove would contain any plutonium within the room. The alcove would be in a situation similar to that of the alcoves for the Holog, Bagpipe, or Clarinet tests, which were permanently sealed with concrete following the experiments. Lawrence Livermore managers note that no plutonium has ever been released from an experimental area.

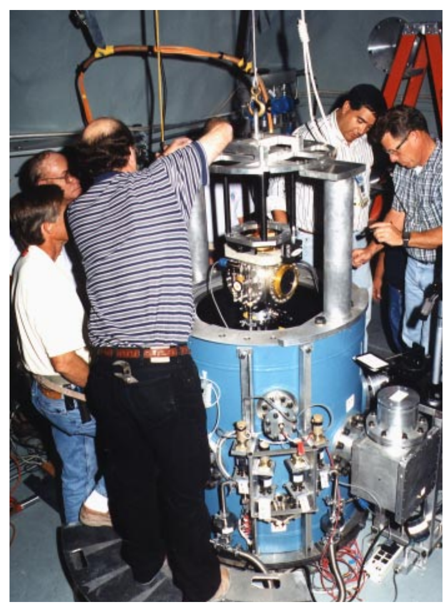
All underground areas and all personnel are monitored for radiation exposure. Workers are not allowed into the reusable alcoves following an experiment until detectors show that there has been zero leakage of plutonium from the experimental steel vessel.

Once lowered downhole, a confinement vessel for the Oboe test series is transported to the experimental alcove. The vessel is designed to confine the gases and radioactive debris generated by a typical experiment.

The vessels with 3-centimeter-thick walls were designed by an engineering team from Lawrence Livermore and Bechtel Nevada. They measure 1.2 meters long and 1 meter in diameter, compact enough to move through the crawl tube of the containment barrier separating the alcove from the corridor. Computer simulations were used to design and test the vessels to ensure that they would reliably confine the detonation products. The design was then experimentally tested at the High Explosives Applications Facility at Lawrence Livermore and the Big Explosives Engineering Facility at the Nevada Test Site. In addition, each newly constructed vessel is pressure-tested to 42 kilograms force per square centimeter, a more-than-adequate pressure to confine the gases and radioactive debris generated by the typical experiment.

Once a new vessel is transported into the alcove, a “cube”—an experimental package containing plutonium and

The steel vessel is pulled through the entryway into the experimental alcove.



Livermore and Bechtel Nevada workers lower the “cube,” which contains plutonium and chemical explosives, into the heavily instrumented vessel.

chemical explosives—is lowered inside. The vessel and the cube are typically maintained at different atmospheric pressures. The vessel is only moderately evacuated; residual air pressure is used to lessen the shock of exploding debris. The cube is at a much lower pressure to permit a laser beam to penetrate the exploding plutonium without being diffracted by air molecules.

Concrete Entombs Vessels

Conrad says the expendable vessels have resulted in significant cost savings and improved data return. "The vessels permit turnarounds faster than anyone had believed possible," he adds. Oboe experiments, for example, have been performed about every six weeks, at a much lower cost per experiment. "With expendable vessels, we can learn from one shot and apply it to the next experiment just a few weeks away," he says.

Conrad notes that Holog, Bagpipe, and Clarinet each were fired as clusters of experiments in dedicated alcoves. It took about one year to complete mining activities for the separate alcoves and to set up each experiment cluster, with much of the diagnostic equipment installed in the same room. (Image recording had to rely on sophisticated optical-relay systems connected to equipment outside the alcove.) After the experiment, each alcove and its resident diagnostic equipment were permanently contaminated from the detonation and could not be reused.

By significantly reducing the need for new alcoves, the vessels save mining costs of about $20 million and double the usable lifetime of the 102 minicomplex from two years to four. Scientists expect to stage up to 12 Oboe experiments in the first alcove of this minicomplex before they start running out of room from the accumulation of entombed vessels. Then, they plan to fire the first Piano shot because it is possibly too powerful to be confined within a vessel. After that, the alcove will be permanently sealed, as was done with the Holog, Clarinet, and Bagpipe alcoves, and experimenters will move on to the next alcove.

Conrad notes that the new format allows diagnostic data to be recorded either inside or outside of the alcove, depending upon the experimental configuration. Some data may be transmitted over electrical or fiber-optic cables to recording instruments outside the alcove, while other data are recorded inside the room and retrieved following the experiment.

For example, holography film is placed next to the high-resolution lens of a viewing port of the vessel. By locating the film very close to the experiment, scientists have obtained Oboe holograms with unprecedented quality and without the cumbersome optical-relay system used on Holog, Clarinet, and Bagpipe.

Lawrence Livermore physicists have been pleased with the data obtained from subcritical tests and how they are allowing colleagues to refine advanced simulation codes that run on supercomputers. Lear says experimenters are particularly pleased with how well the expendable vessel concept has worked.

The subcritical tests are envisioned to continue for the foreseeable future as experimenters gain confidence and experience. Mining has begun on an addition, called the 104 minicomplex, to accommodate experiments planned for the middle part of the decade. Those experiments will also be named after musical instruments. Livermore scientists hope these tests will continue to produce data that are music to their ears.

—Arnie Heller

Key Words: Big Explosives Engineering Facility, Device Assembly Facility, ejecta, High Explosives Applications Facility, Integrated Safety Management, Nevada Test Site, plutonium, Site 300, spall, stockpile stewardship, subcritical tests, U1A complex.

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DAVID C. CONRAD is the test director for the Nevada Experiments and Operations Program. He provides project planning, coordination, and integration of multidisciplinary teams for the execution of tests, projects, demonstrations, and experiments at the Nevada Test Site. He served as the test director on Holog, the first subcritical experiment to be conducted by Lawrence Livermore. Conrad received a B. S. in electronics engineering from Mississippi State University and an M.S. in electronics engineering from the Georgia Institute of Technology. At Lawrence Livermore since 1978, Conrad has had various assignments and managerial positions, including technical coordination of the separator controls for the Atomic Vapor Laser Isotope Separation project and operations management of Livermore's Industrial Partnerships and Commercialization Program. He has also served as U.S. technical expert for treaty verification negotiations in Geneva and Moscow.